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13. ABSTRACT *(Maximum 200 words)*

This project aims at the implementation of a computer-aided diagnosis system for the detection of microcalcifications on mammograms based on the algorithms developed by the principal investigator and others. In addition, the proposed research includes: (1) algorithm improvement for the detection of microcalcifications, (2) mammographic image compression and its impact on computer-aided diagnosis (CADx), and (3) computer-aided classification of benign and malignant masses on mammograms.

In the past year, we have developed several algorithms and have studied part of the proposed research: (a) development of filtering techniques with wavelet transform to reduce mammographic structures other than microcalcifications, (b) performance of preliminary study in the detection of microcalcifications, (c) performance of mammographic compression studies using split gray values in conjunction with wavelet and full-frame discrete cosine transform (DCT) techniques, (d) evaluation of the impact of the compression with respect to various degrees of data compression, and (f) implementation of CADx system in a DEC Alpha workstation.

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The Second Annual Report for Project Titled:

Implementation of Computer Assisted Breast Cancer Diagnosis

(US Army Grant No. DAMD17-93-J-3007)

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The Second Annual Report for Project Titled:

Implementation of Computer Assisted Breast Cancer Diagnosis

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1. Introduction

Recently, several investigators have proposed a number of methods for the automatic detection of microcalcifications and masses on mammograms. Significant improvements in accuracy have been made since the initial attempt [Chan 1987; 1988] to apply the computer algorithms for the detection of microcalcifications. We believe that it is important to implement the program into a high speed workstation and conduct a large scale clinical trial in order to evaluate its clinical practicability and limitations. Although the false-positive rate for the detection of masses is still very high, we have been using an artificial neural network to classify malignant and benign masses. We believe that the creation of a computer program to analyze features of suspected masses will give rise to a more useful and fundamental approach to computer-aided diagnosis.

Because digital mammography produces a large data volume for its high-resolution imaging, data compression is an important means to facilitate the mammographic image transmission and storage. We have studied characteristics of the mammograms and developed compression methods specifically for mammograms using gray value splitting in conjunction with wavelet and full-frame discrete cosine transform (DCT) techniques. Effects of applying the data compression to the proposed computer aided diagnosis (CADx) scheme in the detection of microcalcifications were also tested during this reporting period.

2. Research in the Detection of Microcalcifications

2.1. Detection of Suspected Microcalcifications

Microcalcifications in breast cancer are reported to occur with five or more microcalcifications as a cluster in a $1 cm^2$ area [Black 1965, Fisher 1975]. When the digitization pixel size is 50 µm (using a Lumiscan 150), there are 40,000 pixels in $1 cm^2$ area. To have five detections or pixels (0.0125%) possessing high intensity in the area means that one should set a threshold on pixel intensity approximately 3.61 σ (σ: standard deviation). In one experiment, we used 3.02 σ as the threshold corresponding to a maximum of 50 pixels (0.125% as indicated in Figure 1) due to potential larger microcalcification containing several detected pixels together. Note that a background trend correction was applied to each image block prior to the statistical calculation. The previously detected suspected areas (i.e., 50 pixels) were masked with the mean value in this detecting procedure. This procedure was

performed with a $1cm^2$ template (200×200 pixels) by moving 190 pixels per step for each operation and by scanning through the mammogram horizontally and then vertically.

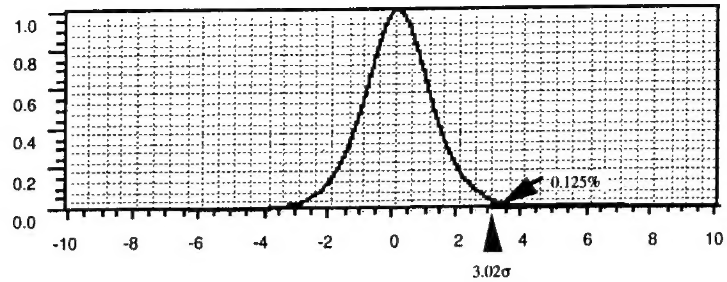

Figure 1. Assuming the noise spectrum fits Gaussian distribution, only 0.125% of pixels have an intensity higher than 3.02 σ.

After carefully evaluating twenty-two mammograms containing subtle microcalcifications (only three clustered microcalcifications on three mammograms were associated with malignant process), we found that the use of 3.02 σ for the threshold value was fine except for radiolucent regions (OD > 2.3) where a threshold value should be set at 2.75 σ corresponding to 120 pixels (0.3%) in 1 cm^2 area. In addition, when a large area was detected (> 30 pixels) then additional pixels corresponding to the area would be granted in the local operation. Our results indicated that all microcalcifications (27 clusters confirmed by biopsy and 126 singles were confirmed by an experienced radiologist) were detected through the above procedure. However, an average of 858 suspected areas per mammogram was obtained (i.e., 99.5% false-positive rate for 100% true-positive detection). <u>This procedure is equivalent to a pre-scan process of a computer-aided diagnosis in the detection of microcalcifications [Chan 1987; 1990]. The important point here is that we have developed an effective computer program that can detect all microcalcifications. It takes 5-7 seconds in a DEC Alpha computer to run a digital mammogram of $4,096\times5,120$ pixels. The suspected areas will be used for the further evaluation of CADx using more strait criteria and in the mammographic image compression for error handling in the next section.</u>

3. Adaptive Lossless Mammographic Image Compression

We have also developed an adaptive lossless compression scheme for mammograms by combining a high compression method and techniques involving the detection of all suspected microcalcifications to ensure data accuracy in the clinically significant areas. In the previous section, we described how to detect suspected microeocalcifications. To handle 858 suspected areas is not a big task at all when compared to the compression of a $4K\times5K$ mammogram (see section 3). However, we can preserve the maximum data accuracy on clinically significant areas. This type of error control should be used in any medical image compression scheme when possible.

<u>3.1. Mammographical Image Compression via Wavelet Decomposition</u>

Recently, we have used a wavelet transform for mammographic image compression [Daubechies 1988, Mallat 1989, Cody 1992, Atonini 1992]. Before the wavelet transform, the boundary of the breast was outlined. Only the area within the boundary was the area to be compressed. Figure 2 shows a typical multi-level wavelet transform and the associated compression procedure. The larger the image, the more levels of wavelet transform can be applied. In general, "A" contains a much smaller computer space than "B" and "A" space + "B" space is about $4K \times 5K \times 3$ bit (a compression ratio of 4:1). If the air region is included in the compression process, the average error-free compression ratio is ≈2.5:1.

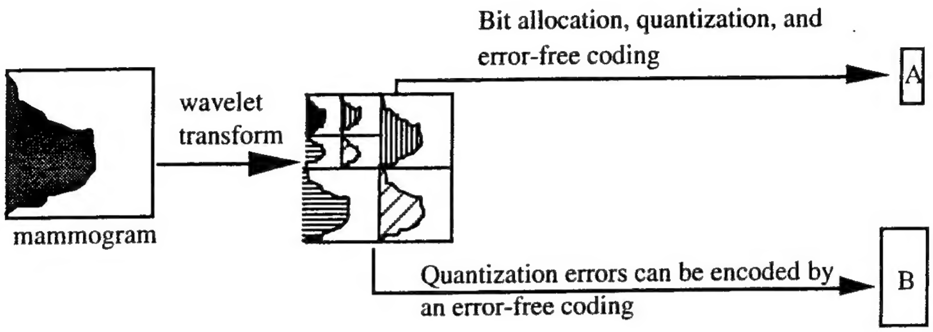

Figure 2. A typical wavelet decomposition and associated compression procedure for a mammogram. (Note: only a two-level decomposition is shown.)

In this study, we decomposed each image with 7-level wavelet transform; hence, the smallest size image will be a matrix of 128×160 pixels. The lowest resolution subimage will be further decomposed by an operation called deferential pulse code modulation (DPCM). The entropy of the all-decomposed subimages will be calculated to determine the best wavelet kernel for the mammographic image compression.

3.2. Error-Controlled Compression for Digital Mammograms

We believe that an accurate error-control procedure is an innovative solution to make a compression scheme clinically useful. A computer scheme for the compression was tested and is described as follows:

(a) Detect all suspected microcalcifications (clusters and singles) based on the method described in Section 2.

(b) Perform an error-free compression using DPCM and arithmetic coding on the detected areas. Replace the area with surrounding intensity using cubic spline interpolation.

(c) Perform multi-level wavelet transform for the mammogram.

(d) Perform quantization on the wavelet domain (For the higher level of low resolution subimages the less destructive quantization should be applied.)

(e) Perform an entropy coding on quantized subimages to get file "A" indicated in Figure 1. (arithmetic coding [Witten 1987] for uncorrelated coefficients and L-Z coding [Ziv 1978] for correlated data sequence.).

3.3. Experimental results

The unique point of this work is to add the error-free feature for the suspected disease areas to a compression scheme. No compression artifact shall be observed by an experienced breast radiologist. One must realize that there is no need to digitize a resolution as high as 50μm/pixel except those areas containing subtle microcalcifications. However, the error control feature reduced some degrees of the entire compression efficiency (ratio). Equation (1) provides a formula to calculate the effective compression ratio when the error-control feature is added into the compression system.

$$R_t = \frac{R \times R_e \times T}{(R - R_e) \times N \times S + R_e T} \quad \ldots(1)$$

where T is the total number of pixels in the original mammogram, S is the number of pixels in the suspected area for error-free encoding, N denotes number of suspected areas, R is the compression ratio obtained by performing a transform (wavelet) coding, R_e is the average compression ratio to error-free encode microcalcification areas, and R_t is the total effective compression ratio.

We tested the same twenty-two mammograms as used in Section 3. We calculated the effective compression ratio by providing values:

$N \approx 858$;

$S \approx 640$ ($\approx 25 \times 25$ pixels) which was averaged from 81% tiny suspects requiring 20×20 pixels (i.e., $1\text{mm} \times 1\text{mm}$ area) and 19% medium-sized suspects requiring 40×40 pixels;

$T = 20{,}971{,}520$ ($4{,}096 \times 5{,}120$);

$R_e \approx 2.5$;

$R \approx 40{:}1$ (estimated acceptable compression ratio) which is partly due to the fact that $\approx 50\%$ of mammogram contains air space.

Substituting the above values into Equation (1), we received $R_t \approx 29$ which also indicates that an additional 40% of the compressed data was increased when the error-free feature was added to the compression scheme. Since each 12-bit datum is stored in a 16-bit computer space, R_t was 38 for current commercial data systems. Because the suspected areas may contain significant clinical

information, we believe that the error control feature is necessary and is a cost-effective approach for mammography data reduction.

4. Recognition of Mammographic Microcalcifications with an Artificial Neural Network

We have developed a computer-aided diagnosis (CADx) program for automated detection of clustered microcalcifications in digital mammograms. In this study, we investigated the use of a convolution neural network (CNN) in conjunction with the CADx program to reduce false-positive (FP) detections.

Screen-film mammograms containing subtle microcalcifications were digitized with a laser film scanner. After signal-to-noise ratio (SNR) enhancement and background removal with a spatial filter, potential signal sites were detected with a locally adaptive gray-level thresholding technique. The size and contrast were used to discriminate false signals from true microcalcifications. The remaining signals were then inspected by the CNN. Image blocks containing individual microcalcifications in the SNR-enhanced images were input to the CNN. The CNN consisted of nodes organized in groups and the weights connecting the nodes were organized by convolution kernels. These weights integrated neighborhood information for recognition of the true signals. After training, we found that a CNN with two hidden layers, both contained 10 groups of nodes, was effective in the classification of true and false signals. The output signals from the CNN further underwent a regional clustering algorithm for detection of clustered microcalcifications.

We found that the CNN could classify individual microcalcifications with the area under the ROC curve, Az, of 0.88, FROC analysis showed that the addition of CNN classification to the CADx program reduced the false-positive cluster detection by 60-70% for a given true-positive rate. After adding a criteria regarding a minimum of 3 calcifications in one cluster for a detection, the Az was increased to 0.96. These results indicate that the CNN can significantly increase the accuracy of the CADx program.

5. Computer-Aided Diagnosis in Mammography: Classification of Mass and Normal Tissue by Texture Analysis

Computer-aided diagnosis schemes are being developed to assist radiologists in mammographic interpretation. In this study, we investigated if texture features could be used to reliably distinguish between mass and non-mass regions in clinical mammograms. Forty-five regions of interest (ROIs) containing true masses with various degrees of visibility and 135 ROIs containing normal breast parenchyma were extracted manually from digitized mammograms as case samples. Spatial gray level dependence (SGLD) matrix of each ROI was calculated and eight texture features were calculated from

the SGLD matrix. The pair-covariance and class-distance properties of extracted texture features were analyzed.

Selected texture features were input into a modified decision tree classification scheme. The performance of the classifier was evaluated for different feature combinations and orders of features on the tree. A classification accuracy of about 89% sensitivity and 76% specificity was obtained for certain groups of ordered features during the training procedure. With a leave-one-out method, the test result was about 76% sensitivity and 64% specificity. The results of this preliminary study demonstrate the feasibility of using texture information for distinguishing masses from normal breast parenchyma.

6. Classification of Mass and Non-Mass Regions on Mammograms using an Artificial Neural Network

We evaluated the feasibility of using an error-backpropagation based Artificial Neural Network (ANN) classifier to detect mass regions on mammograms. Regions of interests (ROIs), which included masses and normal breast parenchyma, were manually extracted from a database consisting of 87 clinical mammograms. Texture features based on a spatial gray level dependence matrix were calculated and input into an ANN using supervised back-propagation training method. The data were divided into five groups and different combinations of these groups formed four sets of training data and test data. We evaluated the performance of the ANN with different combinations of input features, numbers of hidden layers, and number of nodes in each layer. Using five input features, one hidden layer with ten nodes, and an output layer with two nodes, we achieved on the average a true positive fraction of 84% at a false positive fraction of 34% with an ambiguity rate of 5%. This pilot study paves the way for further studies in classification of different types of masses and normal breast parenchyma when a large data set that includes enough samples for each case becomes available.

7. Status Report in the Implementation of CADx for the Detection of Clustered Microcalcifications

We continue to work on the CADx program with a DEC Alpha workstation. The basic user interface is complete. However, it requires suggestions and modifications from our clinical collaborators. The user interface can select a mammogram and display it on the workstation. Several image functions have been implemented: (1) "window and level" for the adjustment of the brightness and contrast, (2) pan, and (3) a cursor box for the user to select the area of interest. The computer-aided detecting program is nearly complete. Clincal trial will start from February 15, 1995 at the Breast Imaging Division of Georgetown University Hospital.

8. Contractual (SOW) Issues

Dr. R.V. Shah, chief brest radiologist, at Brook Army Medical Center and Dr. Don Smith, attendant breast radiologist, at Madigan Army Medical Center have agreed to send us some proven cases (in the Spring of 1995) associated with mammographic microcalcifications for inclusion in our test database [Private Communication]. We will provide our software for the evaluation at Army Hospitals after they are ready to start the experiment.

9. Conclusions of the Annual Report and Future Work

During the last year, we have spent our effort not only in algorithm improvement but also in merging our newly developed algorithm in C and useful codes previously developed by Dr. Chan and her colleagues.

At this point, we have performed our mammographical image compression and CADx research in terms of algorithm improvement and computer speed. Database collection is underway and will continue up to the final stage of this project. Several basic functions and user interface have been implemented in the workstation. The CADx programs are ready to undergo for a clinical trial.

We will spend most of our research time evaluating the effect of CADx using the proposed computer scheme and continuing compression research including:

9.1. Improvement in the Detection of Suspected Microcalcifications

We plan to improve the algorithm for the detection of suspected microcalcifications indicated in Section 2. Two methods along this research direction will be evaluated:

(i) To isolate large objects (such as ducts, macrocalcifications, isolated mass, and other foreign objects which are radiodense) prior to the statistical analysis of each region. This can be done using a combined technique involving segmentation-based image processing and contour extraction.

(ii) When clustered microcalcifications are found in a given area, the standard deviation threshold level will be decreased (i.e., higher sensitivity level will be set) to include possible low intensity calcifications in the region.

9.2. Effectivenes of the Adaptive Lossless Compression for Mammograms

We anticipate that the decompressed digital mammograms will be reviewed in routine mammographic reading. Contrast enhancement function and magnification view will be used for the viewing the decompressed and difference (between original and decompressed) images. When operating contrast enhancement function, mean level will be driven to a low intensity (say the intensity of the outer boundary of the skin) to investigate low intensity artifacts including possible minor structure changes and

blocky artifacts between a suspected area (error-free encoded) and its surrounding parenchyma. In the investigation of the difference, the objective is to observe any structure. Ideal difference image is a pure random noise excluding the error-free encoded areas both in spatial and frequency domains. We will also use Fourier analysis to investigate each difference image. Quantization levels will be varied to investigate the acceptable threshold using the studies indicated above. Without vigorous technical and clinical evaluations for the proposed compression method, no preset compression efficiency (ratio) will be recommended. These studies will only be used for the adjustment of compression parameters for technical use. A more extensive clinical study involving receiver operating characteristic (ROC) analysis and subjective clinical readings [MacMahon 1991, Swets 1982] will be conducted in a future project.

In addition, we will include the detection of suspected masses in the proposed adaptive compression scheme in our research work for the next year.

References

Antonini M, Barlaud M, Mathieu P, Daubechies I: "Image Coding Using Wavelet Transform," IEEE Trans. Image Proc., vol. 1 No. 2, 1992, pp. 205 - 220.

Black JW, Young B: "A Radiological and Pathological Study of the Incidence of Calcifications in Diseases of the Breast and Neoplasms of Other Tissues," Br J Radiol 1965;38:596.

Chan HP, Doi K, Galhotra S, Vyborny CJ, MacMahon H, Jokich PM: Image Feature Analysis and Computer-aided Diagnosis in Digital Radiography. 1. Automated Detection of Microcalcifications in Mammography", Med. Phys., 1987;14:538.

Chan HP, Doi K., Vyborny CJ, et al.: "Improvement in Radiologists' Detection of Clustered Microcalcifications on Mammograms: The Potential of Computer-Aided Diagnosis," Invest. Radio. vol. 25, 1990, pp. 1102-1110.

Cody MA, "The Fast Wavelet Transform," Dr. Dobb's Journal, April 1992, pp. 16-28.

Daubechies I, "Orthonormal Based of Compactly Supported Wavelets", Comm. on Pure and Appl. Math., Vol. XLI, 1988, pp. 909-996.

Fisher ER, Gregorio RM, Fisher B, Redmond C, Vellios F, Sommers SC: "The Pathology of Invasive Breast Cancer," Cancer 1975;36:1.

MacMahon H, Doi K, Sanada S, Montner SM, Giger ML, Metz CE, Nakamori N, Yin F, Xu X, Yonekawa H, and Takeuchi H: "Data Compression: Effect of Data Compression on Diagnostic Accuracy in Digital Chest Radiography", Radiology, Vol. 178, No. 1, Jan. 1991, pp. 175-179.

Mallat S, "A Theory For Multiresoltion Signal Decomposition: The Wavelet Representation", IEEE Trans. Pat. Anal. Mach. Intel., Vol. 11 No. 7, 1989, pp. 674-693.

Swets JA and Pickett RM, Evaluation of Diagnostic Systems, Academic Press, New York, 1982.

Witten IH, Neal RM, and Cleary JG: "Arithmetic Coding for Data Compression," Comm. of the ACM, Vol. 30, June 1987, pp. 520-540.

Ziv J and Lempel A: "A Universal Algorithm for Sequential Data Compression," IEEE Trans. on Info. Theory, Vol. IT-23, No. 3, May 1977, pp. 337-343.

Presentations and Publications During the 2nd Year of the Project

1. Petrosian A, Chan HP, Helvie MA, Goodsitt MM, Adler DD: "Computer-aided diagnosis in mammography: classification of masses and normal tissue by texture analysis," Physics in Medicine and Biology 1994; 39: 2273-2288.

2. Cheng SNC, Chan HP, Helvie MA, Goodsitt MM, Adler DD, St. Clair D: "Classification of mass and non-mass regions on mammograms using artificial neural network," J. of IS&T 1994; 38: 598-603.

3. Lo SC, Kim MB, Li H, Krasner BH, Freedman MT, and Mun SK, "Radiological Image Compression: Image Characteristics and Clinical Consideration," SPIE Proceedings, Medical Imaging 1994, vol. 2164, pp. 276-281.

4. Wu YC,.Lo SC, Freedman MT, Zuurbier RA, Hasegawa A, Mun SK: "Classification Of Microcalcifications In Radiographs Of Pathological Specimen For The Diagnosis Of Breast Cancer," Academic Radiology, (in press)

5. Lo SC, Chien M, Jong S, Li H, Freedman MT, and Mun SK: "Extraction of Rounded and Line Objects for the Improvement of Medical Image Pattern Recognition," IEEE/MIC Proceedings, Nov. 1994 (in press).

6. Lo SC, Lin JS, Freedman MT, and Mun SK: "Application of Artificial Neural Network to Medical Image Pattern Recongnition," WCNN, INNS Press, 1994, Vol. I, pp.37-42.

7. Lo, S.C., Li, H., Krasner, B.H., and Mun, S.K., "Full-frame Compression Algorithms of Wavelet and Cosine Transform," SPIE Proc. Med. Imaging 1995, (to be published)

8. Lo S.C., Li, H., Freedman, M.T., and Mun, S.K., "Convolution Neural Network with Wavelet Kernel for General Medical Image Pattern Recognition." SPIE Proc. Med. Imaging 1995, (to be published)

9. Chan HP, Wei D, Lam KL, Lo SCB, Helvie MA, Adler DD. Computerized detection and classification of microcalcifications on mammograms. SPIE Proc. Med. Imaging 1995, (to be published)

10. Sahiner S, Chan HP, Wei D, Helvie MA, Petrick N, Adler DD, Goodsitt MM: "Image classification using a convolution neural network," SPIE Proc. Med. Imaging 1995, (to be published)

11. Petrick N, Chan HP, Sahiner B, Wei D, Helvie MA, Goodsitt MM, Adler DD: "Automated detection of breast masses on digital mammograms using adaptive density-weighted contrast -enhancement filtering," SPIE Proc. Med. Imaging 1995, (to be published)

12. Wei D, Chan HP, Helvie MA, Sahiner B, Petrick N, Adler DD, Goodsitt MM: "Multiresolution texture analysis for classification of mass and normal breast tissue on digital mammograms," SPIE Proc. Med. Imaging 1995, (to be published)

Articles Submitted for Publication:

13. Lo SC, Chan HP, Lín JS, Li H, Freedman MT, Mun SK: "Artificial Convolution Neural Network for Medical Image Pattern Recognition," Neural Networks.

14. Chan HP, Lo SC, Sahiner B, Lam KL, and Helvie MA: "Computer-Aided Detection of Microcalcifications: Pattern Recognition with an Artificial Neural Network," Medical Physics

15. Chan HP, Wei D, Helvie MA, Sahiner B, Adler DD, Goodsitt MM, Petrick N: "Computer-aided classification of mammographic masses: Linear discriminant analysis in texture feature space," Physics in Medicine and Biology.

16. Wei D, Chan HP, Helvie MA, Sahiner B, Petrick N, Adler DD, Goodsitt MM: "Classification of mass and normal breast tissue on digital mammograpms: Multiresolution texture analysis," Medical Physics.

17. Petrick N, Chan HP, Sahiner B, Wei D, "An adaptive density weighted contrast enhancement filter for mammographic breast mass detection," IEEE Trans.Medical Imaging.

18. Sahiner B, Chan HP, Petrick N, Wei D, Helvie MA, Adler DD, Goodsitt MM: "Classification of mass and normal tissue on mammograms using a convolution neural network," IEEE Trans. Medical Imaging.